Pupillary Response to False Memories in the DRM Paradigm

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Abstract

The current study investigated pupillary responses to false memories in the Deese-Roediger-McDermott (DRM) paradigm. Despite the extensive research on the neural and behavioral components involved in the false memory phenomenon, no known studies have utilized pupillometry in conjunction with this task. Pupillary responses have been shown to correlate with activity in the locus coeruleus of the brain. Given this nucleus' central importance for neuroadrenergic modulation of cortical activity, pupillometry provides a window on attention processes and memory. Therefore, 30 participants were tested on a recognition version of the DRM with pupillary responses recorded during the testing phase. This study revealed four key findings: 1) pupil responses differ depending on word type presented in the DRM paradigm; 2) seen words were found to elicit a greater pupillary dilation than unseen words (seen > unseen); 3) lures were also found to elicit a larger pupil response compared to the unseen words (lure > unseen); 4) pupil dilation to lure words was greater than those of the seen words, however not significantly different (lure ≥ seen). These findings indicate that the pupil does reveal a memory component and that it is sensitive to attentional processes and cognitive demand. This research helps in understanding the intricate components of memory, the ways in which they can be measured, and how they can be applied to clinical settings.

Introduction

Memory can be subjective, biased, reconstructive, and susceptible to the influence of others (Gallo, 2010; Loftus & Davis, 2006; Schacter, 1999). Memory illusions can go as far as individuals falsely recalling childhood memories of being lost in the shopping mall and of hot air balloon rides, as well as alien abductions and even being exposed to satanic ritual abuse, all by means of suggestion (Loftus & Davis, 2006; Loftus & Pickrell, 1995; Perry, 2006; Wade, Garry, Read, & Lindsay, 2002). These false memories are particularly harmful as they are confidently believed and recollected by the individual. This phenomenon is far more frequent than one might think and a debate termed the “memory wars” has surged within the field of psychology (Loftus & Davis, 2006). Partially due to an influx of adults suddenly retrieving “lost” memories of childhood abuse, researchers began to question whether it was possible to have amnesia for childhood trauma only to be later recovered. This research also raised questions as to the legitimacy of various therapeutic techniques aimed at uncovering these abuse memories, such as hypnosis, suggestive therapies, guided imagery, and recovered memory therapy (Loftus & Davis, 2006).

While this topic has been researched, discussed, and debated for years, there are still unknown factors involved in the creation and maintenance of false memory (Gallo, 2010). This topic has grave significance as it helps in understanding the nature of traumatic memories, factors that influence and contribute to memory distortion, and most importantly, can be applied to clinical and judicial settings. Therapeutic interventions can then adjust and modify their perspectives taking into account the malleability and sensitivity of memory (Loftus & Davis, 2006). In addition, the judicial system can better treat the potential victims of child abuse and their accused perpetrators as well as evaluate eyewitness testimonies.

The field of cognitive neuroscience has taken to this topic and investigated both the behavioral and neural components involved in these illusions (Gallo, 2006, 2010; Schacter & Slotnick, 2004). By studying memory with various techniques in the laboratory, researchers have been able to manipulate and analyze the encoding and retrieval of false memory. Through neuroimaging, electrophysiology, and neuropsychology, similarities and differences to the neural processes of true and false memories have been measured. Specifically, case studies of patients with brain damage have revealed the role of the frontal cortex, the medial temporal lobe, and the parietal cortex in memory recall and recognition (Curran, Schacter, Norman, & Galluccio, 1997; Davidson et al., 2008; Drowos, Berryhill, Andre, & Olson, 2010; Gallo, 2006; Melo, Winocur, & Moscovitch, 1999; Parkin, Bindschaedler, Harsent, &

Metzler, 1996; Schacter, Curran, Galluccio, Milberg, & Bates, 1996a; Schacter & Slotnick, 2004; Schacter, Verfaellie, & Anes, 1997b; Verfaellie, Rapcsak, Keane, & Alexander, 2004; Verfaellie, Schacter, & Cook, 2002). Studies using function Magnetic Resonance Imaging (fMRI) have found activation in the frontal cortex, the visual processing areas, medial temporal lobe, cerebellum, anterior cingulate, precuneus, and the parietal lobe in response to false memory paradigms (Cabeza, Rao, Wagner, Mayer, & Schacter, 2001; Gallo, 2006; Gonsalves et al., 2004; Okado & Stark, 2003; Schacter et al., 1996b; Schacter & Slotnick, 2004; Slotnick & Schacter, 2004). In addition, the event related potential (ERP) technique has demonstrated early medial activity, parietal activity, and late frontal activity to certain parts of memory tasks (Curran, Schacter, Johnson, & Spinks, 2001; Gallo, 2006; Geng et al., 2007; Miller, Baratta, Wynveen, & Rosenfeld, 2001; Nessler, Mecklinger, & Penney, 2001; Schacter & Slotnick, 2004). These studies have illustrated that there are unique neural processes to true memories compared to false, as well as some processes that are similar for both.

Psychophysiological studies have also investigated differences between episodic accounts through the study of deception (Andreassi, 2007). These studies used heart rate, galvanic skin response, respiration, ERPs, and pupillary response in an effort to develop a polygraphic “lie detection” technique. It has been demonstrated that lying causes increased anxiety, cognitive load, and arousal, which can be measured through psychophysiological and ERP measures (Andreassi, 2007). Skin conductance has been found to increase during deception and be an excellent indicator of lying, it can however be inconsistent due to its sensitivity (Andreassi, 2007; Dionisio, Granholm, Hillix, & Perrine, 2001). Increased blood pressure and respiration have been regarded as better measures of deception in real-life situations (Andreassi, 2007). The ERP technique has also been implemented to determine true from false information. Due to the P300 component’s response to relevant stimuli, research has found that it is also indicative of lying (Andreassi, 2007; Dionisio, et al., 2001; Farwell & Donchin, 1991). Such studies use the Guilty Knowledge Test, in which some participants are given privileged information about an event and instructed to withhold certain information. The P300 component is found to respond to the relevant questions about the event in those with the guilty knowledge (Andreassi, 2007).

Pupillometry has also been used as a technique in lie detection, finding pupil diameter increase to be indicative of guilty knowledge (Lubow & Fein, 1996). Pupil response has also been measured to be greater when participants lie about semantic and episodic memory (Dionisio, et al., 2001). There are many inconsistencies within this deception research and debates around its ability to be applied to real-life scenarios; nevertheless, these studies do illustrate the ability to measure memory by means of psychophysiology. It is important to note however, that lying does differ from the false memory phenomenon, as lying is a deliberate act and false memory is unintentional and outside of consciousness.

While there are many studies using various memory illusion techniques coupled with neuroscience measures, there fails to be any research incorporating pupillometry with the study of false memory. This practical and cost-effective method can give insights into the neural and cognitive components of memory distortion. Pupillary response has been shown to be objective, reflexive, and to respond to novel stimuli as well as increase dilation with cognitive load (Aboyoun & Dabbs, 1998; Andreassi, 2007; Hess & Polt, 1960; Kahneman & Beatty, 1966; Metalis & Hess, 1982; Tursky, Shapiro, Crider, & Kahneman, 1969) or with cognitive conflict as in the Stroop effect (Laeng, Ørbo, Holmlund, & Miozzo, 2011). There is evidence that the pupillary response can index implicit memory components for visual stimuli, regardless of explicit memory (Laeng et al., 2007) and that, in active recognition tasks, the pupil dilates to old stimuli more so than new (Võ et al., 2008). In addition, pupillary response has been demonstrated to correlate with activity within several brain regions, notably the prefrontal and anterior cingulate cortex (Sara, 2009). Thus, it is important to continue investigating the neural characteristics related to false memories via pupillary response. By continuing to study this phenomenon and employing a new measure, details regarding how the vision system and memory are connected will become clearer. This may open the field of cognitive neuroscience and clinical psychology to new possibilities for testing, analyzing, and treating memory distortions and those who are affected by them.

The Deese-Roediger-McDermott Paradigm

Much of the past research on the behavior and neurophysiology of false memories has utilized the Deese-Roediger-McDermott (DRM) paradigm, as this has been proven to be an effective method of producing memory distortions (Gallo, 2006, 2010; Roediger & McDermott, 1995; Schacter & Slotnick, 2004). In this paradigm, participants study a series of word lists and are subsequently tested on the recall or recognition of these words. The word lists are semantically related to one another, for example “snow, winter, ice, chilly.” The reason for creating these lists is that the items revolve around a core, semantically-related, lexical term (in this case “cold”) which can then be used as the “critical lure” in the DRM paradigm. When asked to recall these studied words, participants claim to remember the critical lure at a similar rate to the studied words (Gallo, 2006; Roediger & McDermott, 1995). Recognition tests in this paradigm typically include the study words and the critical lures as well as new unrelated words and new weakly related words. Participants tend to identify the lures, at a rate significantly greater than chance, as being old or as previously-seen items. These rates are also higher than the new unrelated and weakly related words (Gallo, 2006; Roediger & McDermott, 1995).

What is interesting about this paradigm and false memory in general, is that participants tend to have recollection or memory for the presentation of the critical lure (Gallo, 2006; Roediger & McDermott, 1995). This has been tested with "remember/know" judgments, a technique originally developed by Tulving to study different subjective states of consciousness (1985). Tulving theorized that episodic and semantic memory have two different types of conscious awareness, autonoetic and noetic. Autonoetic consciousness is the "self-knowing" aspect of episodic memory where the individual is able to remember and describe details of events. Noetic consciousness on the other hand, is semantic memory and when an individual is "knowing" of an event, but is unable to recall specific subjective components (Tulving, 1985).

The two types of consciousness are tested with the remember/know technique used in conjunction with memory tasks (Gallo, 2006; Roediger & McDermott, 1995; Tulving, 1985). Participants are asked to make judgments for the words they responded to as previously seen with either a "remember" or "know" response; with the first signifying the recall of specific details for an event and the latter signifying believing an event occurred despite not being able to recall details. When this technique is employed after the DRM paradigm, participants tend to have significantly high levels of remember judgments for the critical lure (Gallo, 2006; Roediger & McDermott, 1995). This is an important finding as it points to the degree to which false memories are believed to be real and the degree to which this paradigm replicates such beliefs in the laboratory. With respect to Tulving's theory, more remember judgments for the lure indicate that there is an autonoetic consciousness occurring for these false memories, which have been found to be less frequent for the new unrelated words. This distinction between conscious states for word type in the DRM paradigm is important to keep in mind when discussing the behavioral and neural theories of false memory.

Theoretical Frameworks

Due to the extensive research on the DRM paradigm and false memories, an abundance of theoretical accounts exist. Many of these theories overlap in their ideas and speculations as to the causes of and contributions to memory distortion. Therefore, general concepts of these frameworks most relevant to the current study will be summarized below.

The 'source-monitoring framework' (SMF) is typically used to analyze the DRM paradigm as it characterizes memory as having specific features (i.e. temporal, spatial, emotional, perceptual, etc.) and when retrieved, it is these features that help differentiate events and their sources (Johnson, Hashtroudi, & Lindsay, 1993; Mitchell & Johnson, 2009). These features of events enable the individual to distinguish whether the memory originated from an internal or external source. This framework stresses an associative process where the specific characteristics or features of the event are organized and connected. This information is then evaluated and processed to determine the memory's source. The SMF views memory as being both constructive and reconstructive during encoding and retrieval, emphasizing the ability for one to base memories on familiarity and be influenced by bias, beliefs, and subjectivity. The SMF is built on two concepts, heuristics and systematic processes. The former describes the process of judging memories based on familiarity and perceptual detail, where the latter judges on the degree of remember and know values (Johnson, et al., 1993; Mitchell & Johnson, 2009).

In terms of false memories, the SMF presupposes that both veridical and incorrect memories have similar processes and arise from the same cognitive mechanisms (Gallo, 2006; Johnson, et al., 1993; Mitchell & Johnson, 2009). Errors in memory are more likely to occur when distracters are present during encoding or retrieval making source determination difficult. Particular to the DRM paradigm, studying semantically similar words may give rise to the lure words during encoding. This will cause them to be judged as true memories in retrieval, due to misattributing the internal source as external. Memory illusions may occur during retrieval because memory is rarely received with a marker or label with the exact source of the memory, making monitoring difficult with semantically similar lures (Gallo, 2006; Johnson, et al., 1993; Mitchell & Johnson, 2009).

'Dual-process models' focus on two concepts related to memory, familiarity and recollection (Mitchell & Johnson, 2009; Vilberg & Rugg, 2008). While the SMF also takes into account familiarity, dual-process models differentiate recollection from familiarity whereas SMF considers them as subjective concepts and as being on a continuum. Dual-process models also stress the fact that memory arises from remember/know judgments and point to familiarity as the cause of false memories (Mitchell & Johnson, 2009). The 'fuzzy trace theory' is a specific type of dual-process model suggesting that memory can have either a "gist trace" or a "verbatim trace" (Gallo, 2006; Melo, et al., 1999). Gist trace is when the general meaning of words is recalled possibly leading to memory distortion, whereas verbatim trace is the true recollection of events.

Another important theory on false memory that is not entirely different from the dual-process model or the SMF, is the 'activation/monitoring framework' (Gallo, 2006, 2010; McDermott & Watson, 2001; Roediger, Watson, McDermott, & Gallo, 2001). This two-part framework refers to activation as the enhancement of false memories that occurs primarily during the encoding of stimuli (Gallo, 2010). This can be due to the activation of a related lure or other incorrect information. In the DRM paradigm for example, the lure is produced in response to studying the semantically related list words. Within this part of the framework, there are two possible components, one being associative-activation and the other being gist theory. The former refers to the dispersal of representations from items or constructs that are associated to one another. Here, gist is the formation of a summary or central theme of the stimuli that causes activation of items with the same meaning, similar to the gist trace in the fuzzy trace theory (Gallo, 2006, 2010).

The monitoring element of the activation/monitoring framework refers to the reduction of false memories and most often occurs in the retrieval of memory (Gallo, 2010). This process is best described as a decision-making procedure, taking place when a memory is retrieved and must be evaluated for source information. During retrieval, the stronger the recollection is for true memories, the less susceptible one is to false memories. This is explained by monitoring during retrieval, which assesses the strength of the memory; if the true memories are strong, than the lures will be easier to detect. Monitoring is not exclusively an activation/monitoring framework concept as it shares similarities with the evaluation process in the SMF (Gallo, 2010).

Neural Components

In order to fully understand the theoretical frameworks of false memories discussed above, researchers began to focus on the neural correlates associated with this phenomenon. The evidence from neuroimaging, electrophysiology, and neuropsychological studies shows that there are specific neural components involved in the DRM paradigm that vary according to the word type presented (Gallo, 2010; Schacter & Slotnick, 2004). Several theories aim to explain these neural differences between true and false memories, however many of the exact underpinnings are still unknown.

The ‘sensory-reactivation hypothesis’ was developed from the behavioral findings that true memories tend to coincide with more perceptual and sensory details (Schacter & Slotnick, 2004; Slotnick & Schacter, 2004). This theory suggests that an increase of memory for perceptual detail must be represented in the brain with increased activation to true memories compared to false. Moreover, the brain regions that activate during the encoding of sensory information will conceivably reactivate during the retrieval of these details. As these features do not accompany false memories, they should be distinguishable from true events at the neural level and be able to be measured with neuroscience techniques (Schacter & Slotnick, 2004; Slotnick & Schacter, 2004).

The activation-monitoring framework can also be applied to understanding the neurophysiology of memory illusions (Gallo, 2010). As previously discussed, this framework stresses two elements involved in the formation of true and false memory. Related to neuroscience, this theory aims to identify the neural components involved in activation of the critical lure as well as what monitors the decisions made during retrieval (Gallo, 2010).

Electrophysiology. Since the development of the DRM paradigm, electrophysiology has been used by researchers to study the neural activity of false memories, the majority employing the ERP technique (Gallo, 2006). The excellent temporal resolution with this methodology makes it ideal for understanding the timing of false memory during both encoding and retrieval (Schacter & Slotnick, 2004).

Three common ERP characteristics have been suggested from the past research regarding false memories (Gallo, 2006; Geng, et al., 2007; Schacter & Slotnick, 2004). The first common feature is medially located and occurs early on, around 300-500 ms (Gallo, 2006; Geng, et al., 2007; Nessler, et al., 2001). This activity has been interpreted to reflect a familiarity component, as it is more negative for new unrelated words than for studied words and lures (Geng, et al., 2007). This indicates that because the lure is semantically related to the studied words, it is neurophysiologically interpreted as being familiar (Nessler, et al., 2001).

A second commonality is a parietal effect (Gallo, 2006; Geng, et al., 2007; Miller, et al., 2001; Nessler, et al., 2001; Schacter & Slotnick, 2004). This component occurs approximately around 400-800 ms and tends to be more positive for true rather than false memory (Geng, et al., 2007). It has been extensively documented that this parietal component has an 'old/new effect,' meaning that there is more positive activity at this point and time for stimuli that are recollected (Rugg & Curran, 2007). This effect suggests that during retrieval there is recollection of the perceptual details of the studied word, but not for the lure or the new, unrelated word (Geng, et al., 2007; Miller, et al., 2001; Nessler, et al., 2001; Schacter & Slotnick, 2004). Interestingly, this parietal old/new effect has been demonstrated to be affected by behavioral performance when participants are divided into groups of "good" performers with low false recognition rates, and "poor" performers with high inaccuracy rates (Nessler, et al., 2001). It was found that the better performers had old/new parietal effects for true memories but not false, whereas poorer performers had similar parietal old/new effects for true and false recognition. It was speculated that these ERP results were due to the higher performers' superior encoding strategies (e.g., memory of conceptual details of the item) (Nessler, et al., 2001).

The third similarity in past ERP studies is a late right frontal positivity at around 800-2000 ms (Gallo, 2006; Geng, et al., 2007). This has been demonstrated to be affected by test performance as well, with better performers having increased right frontal ERPs compared to poor performers (Curran, et al., 2001). As frontal regions have been shown to be involved in higher cognitive functions like control and executive processes, activity in this area is presumed to signify a monitoring process that the better-memory performers may engage in more thoroughly, thus reducing error rates (Curran, et al., 2001; Gallo, 2006; Geng, et al., 2007). This later activity may also be considered an indication of evaluation and processing of the stimulus to assess whether it has been observed (Geng, et al., 2007; Nessler, et al., 2001).

The sensory-reactivation hypothesis has been supported through electrophysiology research (Schacter & Slotnick, 2004). By presenting participants with the DRM word lists on either the right or left side of the screen during the study phase and subsequently presenting the words centrally during recognition testing, Fabiani, Stadler, and Wessels found lateralization effects with ERP (2000). They found that correct recognition caused lateralized brain activity in central and posterior sites, but showed no significant lateralization for falsely recognized words. These findings indicate the existence of a neural trace for the stimulus' laterality that was formed during memory encoding and then reactivated during retrieval (Fabiani, et al., 2000; Gallo, 2006; Schacter & Slotnick, 2004).

In further support of this hypothesis, a study using electroencephalography (EEG) found that gamma waves during encoding in the hippocampus, left temporal lobe, and prefrontal cortex were the same during the retrieval of true memories but not false (Sederberg et al., 2007). Sensory-reactivation was also demonstrated when words were paired with pictures, finding that true memories yielded greater posterior positivity compared to false (Gonsalves & Paller, 2000). According to the authors, this finding signifies that true memories have more detailed perceptual information that is reactivated and retraced; a theory that is further supported by the parietal effect to false memories (Geng, et al., 2007; Gonsalves & Paller, 2000; Miller, et al., 2001; Nessler, et al., 2001; Schacter & Slotnick, 2004).

While the majority of studies focus on memory distortion during retrieval, some have measured ERPs during encoding (Gallo, 2006; Geng, et al., 2007; Gonsalves & Paller, 2000; Urbach, Windmann, Payne, & Kutas, 2005). These researchers have found positive waveforms during encoding in words that elicited false memory for the lure during the recognition phase. This suggests that true recognition may be due to stronger memory formations during encoding, as indicated by waveforms that are more positive. These studies are important because they support a dual-process approach to memory falsification and indicate that inaccuracies can occur at both the encoding and retrieval stages of memory (Geng, et al., 2007).

Neuroimaging. Neuroimaging has helped to expand the understanding of false memories in the DRM paradigm by identifying brain regions more precisely than the abovementioned ERP studies. Despite some discrepancies within the literature, positron emission tomography (PET) and fMRI have been used to single out the differences and similarities between true and false memory formation and retrieval, supporting theories of sensory-reactivation and activation/monitoring (Cabeza, et al., 2001; Gallo, 2006; Gonsalves, et al., 2004; Mitchell & Johnson, 2009; Okado & Stark, 2003; Schacter, Buckner, Koutstaal, Dale, & Rosen, 1997a; Schacter, et al., 1996b; Schacter & Slotnick, 2004; Slotnick & Schacter, 2004; Stark, Okado, & Loftus, 2010).

Using PET, Schacter et al. (1996b) revealed that both true and false word recognition increased blood flow in the left medial temporal region, an area associated with episodic memory. Differences were also found. True memories caused an increase in blood flow in the tempoparietal cortex, an area associated with phonological and auditory details. False memories on the other hand, increased blood flow in the prefrontal cortex, the cerebellum, and the orbitofrontal cortex. This was followed by a similar study using event-related fMRI with blocked testing, finding increased activation in the right anterior prefrontal to false memory (Schacter, et al., 1997a). This activity was relatively late, possibly reflecting monitoring of decision-making.

Increasing sensory stimulation has also enabled researchers to successfully measure activation differences between true and false memories with fMRI (Cabeza, et al., 2001). One such study found activation in the medial temporal lobe (MTL) to both veridical and illusory recognition, however, upon further analysis found dissociation within this region. While the hippocampus displayed similar activation to both true and false memories, there was increased activation in the parahippocampal gyrus in response to true memories but not false. The authors argued that the MTL expresses two contradicting signals, with the posterior MTL indicating that the false words are semantically related to the true words, and the anterior MTL indicating that the false items are new sensory stimuli. There was also a dissociation found in the prefrontal cortex (PFC) (Cabeza, et al., 2001). While true and false recognition were associated with increased activation bilaterally compared to the unrelated new words, the left ventrolateral PFC showed more activation for new words than for true or false recognition. This study also corroborated Schacter et al.'s (1996b) findings regarding the obitofrontal cortex and cerebellar regions exhibiting more activation for false memory than true.

Slotnick and Schacter (2004) further developed the sensory-reactivation hypothesis after finding activation differences in the visual cortical area. This study implemented a memory paradigm where participants studied shapes and subsequently performed a recognition test where the original shapes were presented along with new unfamiliar shapes and new similar shapes (lure). The results showed that true and false recognition both elicited activation in the late visual processing regions whereas true memories were found to be associated with increased activation in the early visual processing areas (Brodmann's areas 17 and 18). These authors interpreted their findings to indicate that the early visual processing activation signifies implicit memory where the late visual processing indicates explicit or conscious memory. True shape recognition was also found to cause greater activation in prefrontal, parietal, and motor processing regions compared to false.

Studies have also found the anterior cingulate cortex (ACC) to activate during false memory paradigms (Gonsalves, et al., 2004; Kuehnel, Mertens, Woermann, & Markowitsch, 2008; Nessler, et al., 2001; Okado & Stark, 2003). In an imagery paradigm, participants were exposed to a series of words and instructed to visually imagine the word shown (Gonsalves & Paller, 2000; Gonsalves, et al., 2004). For half of these words, a picture was displayed directly after the word presentation. The test phase consisted of verbal questioning as to whether or not the participant saw an actual picture of the word. The words imagined during encoding that led to later false memory were associated with increased activation in the ACC (Gonsalves, et al., 2004). The right ACC has also revealed activation during the retrieval of false memory in other imagery paradigms (Okado & Stark, 2003). This finding is indicative of required effort needed to process false memories, as the ACC plays a role in monitoring errors. In addition, ACC activation could signify that attempting to locate a false memory requires more effort and results in conflict monitoring (Kuehnel, et al., 2008).

The studies discussed highlight the various differences between true and false memories and how they can be measured using neuroimaging techniques (Cabeza, et al., 2001; Gallo, 2006; Gonsalves, et al., 2004; Okado & Stark, 2003; Schacter, et al., 1997a; Schacter, et al., 1996b; Schacter & Slotnick, 2004; Slotnick & Schacter, 2004). While the exact processes are still uncertain, the MTL, ACC, PFC, and visual cortical area appear to be involved in memory illusions, with the MTL connected to generating false memories and the PFC related to their reduction (Schacter & Slotnick, 2004). The aforementioned studies demonstrate how beneficial it can be to measure brain activation with neuroimaging, yet there are still several limitations with this methodology. Evidence from neuropsychology, therefore, can help to answer some of the unresolved issues from electrophysiology and neuroimaging studies.

Neuropsychology. Case studies involving patients with brain damage allow researchers to measure and examine the consequences of dysfunction to certain brain regions involved in false memories. While there are obvious drawbacks and limitations to this type of study, they have supported several of the findings discussed above (Gallo, 2006; Schacter & Slotnick, 2004). By measuring memory distortion in patients with brain lesions, brain damage, and neurological diseases and disorders like Alzheimer's and Korsakoff's syndrome, these studies have demonstrated a network of brain regions involved in the false memory phenomenon (Schacter & Slotnick, 2004). These include the MTL, the frontal lobe, and recently the parietal lobe (Budson, Daffner, Desikan, & Schacter, 2000; Budson et al., 2002; Curran, et al., 1997; Drowos, et al., 2010; Gallo, 2006; Melo, et al., 1999; Parkin, et al., 1996; Schacter, et al., 1996a; Schacter & Slotnick, 2004; Schacter, Verfaellie, Anes, & Racine, 1998; Verfaellie, et al., 2004; Verfaellie, et al., 2002).

The MTL has been shown to be involved with episodic memory; therefore neuropsychological research began by measuring memory illusions in patients with damage to this area (Gallo, 2006; Schacter & Slotnick, 2004; Schacter, Verfaellie, & Pradere, 1996c). In a false memory recall paradigm, Melo et al. (1999) found MTL amnesic patients recalled more lures than controls. This signified that the patients relied on gist for recall as their memory for specific details was so degraded Two minutes later however, patients recognized fewer studied words and fewer lures than controls on recognition tests. The authors interpreted this as resulting from the time elapse, during which gist memory was severely reduced. This also indicates that the MTL is involved in semantic memory as well as general word recognition (Schacter, et al., 1996c).

Reduced false recognition of lure words in MTL patients has been demonstrated to change over several test trials (Budson, et al., 2000). Alzheimer patients, who suffer from amnesia and damage to the MTL as well as other regions, showed increased false memory after five trials, whereas the control subjects were able to reduce their mistakes. The non-patient group was able to learn over time how to control incorrect gist memory by strengthening specific memory for studied words. Those with Alzheimer's, however, were unable to reinforce their memory over trials for the studied words, and therefore were more prone to relying on intensified gist memory (Budson, et al., 2000).

Gist memory has been further evaluated in amnesic patients by employing a modified version of the DRM paradigm (Verfaellie, et al., 2002). In the testing phase of this paradigm, participants were asked to respond whether a word was "old" or "new." To be deemed "old," the word just had to be semantically related to the studied words. The amnesic participants performed significantly worse on this gist recognition paradigm, indicating that MTL damage impairs memory for gist representations and not just specific item memory.

Neuropsychological studies involving false memories have also measured behavioral differences in patients with frontal lobe damage; thus revealing the involvement of the frontal cortex in memory illusions and further supporting the neuroimaging and electrophysiology studies described above (Gallo, 2006; Melo, et al., 1999; Parkin, et al., 1996; Schacter, et al., 1996a; Schacter & Slotnick, 2004; Verfaellie, et al., 2004). Patients with damage to the right and left frontal lobe were found to have memory for studied words comparable to that of the controls, however with significantly higher amounts of false lure recognition (Curran, et al., 1997; Parkin, et al., 1996; Schacter, et al., 1996a; Schacter & Slotnick, 2004). Notably, false memory was also accompanied by a remarkable confidence when asked to reply with remember/know judgments, an atypical response. In addition, false recognition was eliminated when new unrelated words were added to the word lists in the study phase, signifying that frontal patients relied on generalizations and the gist of words more so than controls.

These same findings related to increased false memory were found in patients with damage to the dorsolateral prefrontal cortex (DLPFC) (Budson, et al., 2002). Interestingly, after five trials, these patients continued to have heightened false recognition, as compared to the control subjects, who were able to reduce theirs. The DLPFC has been implicated in monitoring, allowing researchers to assume that, in patients with damage to this area, the ability to employ this decision-making process was impaired (Budson, et al., 2002). It is important to note that while studies on frontal patients have found similar behavioral results, the exact anatomical components within the frontal lobe have yet to be identified, as patients with damage to certain areas within this structure both share and differ in false memory behavior (Verfaellie, et al., 2004).

Recently, neuropsychological evidence has also found that patients with damage to the posterior parietal cortex can show altered memory distortion (Davidson, et al., 2008; Drowos, et al., 2010). Davidson et al. (2008) tested memory deficits in five patients with lateral parietal damage finding that despite having no amnesia, the patients showed dysfunctional memory recollection. A sixth patient, who suffered from unilateral damage to the posterior parietal cortex, was found to have decreased true and false memory on the DRM paradigm. This patient also had reduced remember judgments in the remember/know paradigm. Drowos et al. (2010) extended these findings to two other patients with damage to the posterior parietal cortex, who were found to have reduced false memory along with reduced recollection. The patients from both studies showed similar behavior performance on the DRM as those with damage to the MTL, despite not suffering from amnesia (Davidson, et al., 2008; Drowos, et al., 2010). It should be noted that these studies are new and bare further investigation, however they point to the involvement of the parietal cortex in memory illusions and help to explain findings from neuroimaging and electrophysiological studies on this brain region.

Pupillometry

The studies reviewed thus far on the neural components implicated in false memory show the complex and intricate processes involved therein. It is also clear that there are certain areas of the brain that respond to specific word types during recognition tasks, with true and false memories differing in some ways and being similar in others. While pupillometry is not as direct a measure of neurophysiology as fMRI or ERP, this method does give insights to neural and cognitive processes. Specifically, recent studies have demonstrated a strong correlation between pupillary response and activity in the locus coeruleus (LC) (Sara, 2009). This nucleus in the brain stem is the main source of noradrenaline and is strongly connected to most other brain regions. The reciprocal relationship between the LC and the prefrontal cortex is relevant to this study; in this relationship, the locus coeruleus and norepinephrine (LC-NE) system receive direction from the prefrontal regions, and in turn the prefrontal regions need adequate levels of norepinephrine for normal cognitive functioning (Corbetta, Patel, & Shulman, 2008; Sara, 2009). Due to this relationship, as well as the LC's affect on increasing the integration of brain networks, the LC-NE system plays an important role in working memory, decision-making, attention, and memory formation and retrieval (Sara, 2009).

In terms of attention, the LC-NE system has both phasic and tonic properties that involve directing attention to salient, novel, and behaviorally significant stimuli, as well as filtering out irrelevant stimuli while performing demanding tasks (Corbetta, et al., 2008; Sara, 2009). The LC-NE system is believed to give input to the ventral frontoparietal network, which is responsible for reorienting attention to relevant and salient stimuli. Moreover, this network will redirect attention to stimuli outside of the task if they are relevant. In this way, the LC-NE system may facilitate the shifting of attention with phasic LC response acting as a reset or an "interrupt signal" (Corbetta, et al., 2008; Sara, 2009).

Noradrenaline, when released from the LC, controls pupil dilation through alpha-2 receptors; the reason why pupil dilation is highly correlated with LC activation and is a reliable representation of LC activity (Sara, 2009). This relationship has been tested in relation to attentional focus and found to be associated with spontaneous perception switching (Einhäuser, Stout, Koch, & Carter, 2008). Measuring pupillary response in participants viewing an ambiguous shape, researchers found that pupil diameter increases directly before a perceptual shift.

The LC-NE system is also important in long-term memory consolidation as well as memory retention, with retrieval of recent information dependent on noradrenaline (Sara, 2009). Correlation between pupillary response and LC activity has also been shown during memory tests (Sterpenich et al., 2006). Participants exposed to neutral faces in neutral and emotional contexts were recorded with fMRI and pupillometry. Emotional reactions were measured by increased pupil dilation during encoding and found to correlate with LC activity during retrieval. The LC showed no significant activation during retrieval when there was no pupil diameter increase. This study suggests several important points; the first of which is the direct correlation between the LC and pupil dilation. Second, is the role of both of these components in the retrieval of memory, specifically emotional memory. This is supported by the anatomical properties of the LC as it connects with the amygdala and has influence, through NE, on memory by way of the hippocampus and the amygdala (Sara, 2009).

This important link between pupillary response and LC activity helps to reinforce and reaffirm studies that use this method to measure and demonstrate the pupil's connection with attention, emotion, memory, and cognition (Andreassi, 2007; Cacioppo, Tassinary, & Berntson, 2007; Dionisio, et al., 2001; Hess & Polt, 1960; Sara, 2009; Võ, et al., 2008). While there are no known studies using pupillometry accompanied by memory illusion paradigms, the studies discussed earlier on "lie detection" as well as those presented below, show the ability of pupillometry to index various cognitive processes.

Early studies discovered that pupils are part of the startle reflex and dilate to salient stimuli, such as an alarming noise (Andreassi, 2007). This led Hess and Polt (1960) to test and illustrate that pupil dilation increases in response to the interest value of stimuli. These researchers observed pupillary response to photographs of nude men or women as well as neutral photographs (landscapes) and photographs of babies. The results showed women to have a greater increase in pupil dilation than men to photographs of babies, while opposite-sex nudity elicited large responses in both men and women. This was interpreted to mean that pupillary change correlates to the interest value of the present stimuli. This concept has been replicated to other scenarios, for example pupil response to taboo words (Aboyoun & Dabbs, 1998; Andreassi, 2007; Hess & Polt, 1960).

These early findings led researchers to speculate that the pupil responds to sexually explicit stimuli (Andreassi, 2007; Hess & Polt, 1960). With further evaluation, however, it has been proposed that pupillary responses are more indicative of novelty than merely sexuality itself (Andreassi, 2007). This view was formulated after finding that heterosexual females also display pupil dilation to nude females and heterosexual males to nude males, and not just to the opposite sex. While these findings were found decades ago, the results were replicated more recently and confirm the probability that pupillary response to nudity is more attributable to the novelty of the images than to their sexual nature (Aboyoun & Dabbs, 1998). In this study, heterosexual males and females viewed pictures of nude females, nude males, clothed males, and clothed females. Pupil dilation was largest for both genders when viewing nude males and most constricted when viewing clothed females. This supports the novelty theory, seeing as the sight of nude men is more unfamiliar in society (as they are least represented in the media and clothed females are the most commonly represented) (Aboyoun & Dabbs, 1998).

Pupil dilation has also been demonstrated to respond to cognitive load and attention processes (Andreassi, 2007; Dionisio, et al., 2001; Kahneman & Beatty, 1966; Laeng, et al., 2011; Porter, Troscianko, & Gilchrist, 2007). This has been found in working memory tasks where an increase in difficulty coincides with an increase in pupil dilation (Andreassi, 2007). Similar effects are also seen in mental multiplication tests, short-term recall, and have even been observed on scholastic aptitude tests where poorer performers have increased dilation due to intensified cognitive effort (Andreassi, 2007).

Another pertinent study regarding memory and pupillometry was conducted on three amnesic patients with damage to the hippocampus (Laeng, et al., 2007). While these patients showed severe deficits in explicit memory recognition, they exhibited increased pupil dilation to novel pictures compared to previously presented pictures. These results highlight several key findings. First, increased pupil dilation to new novel stimuli supports the studies described earlier and suggests that the pupil has the ability to index the memory of an item. Moreover, this response to stimuli is automatic and implicit, it may even involve neural processes outside of the hippocampus and outside of explicit memory. As pupillary response is controlled by the autonomic nervous system and is adaptive in nature, it appears that despite awareness, the pupil can differentiate between old and new pictures and indeed has a memory component (Laeng, et al., 2007).

The findings on the correlation of pupil dilation with cognitive demand, as well as the research described above on the old/new parietal effect in ERP studies, have led to the investigation of an "old/new effect" in pupillary response (Heaver & Hutton, 2010; Võ, et al., 2008). Measuring the effects of emotional valence and cognitive load, Võ et al. (2008) used pupillometry during a recognition task. While the primary objective was to investigate the effect of emotion on pupillary response, the researchers also tested whether studied words produced increased dilation compared to unstudied words in the recognition phase. They argued that as with ERP studies, there might be an old/new effect with pupillary response where increased dilation occurs to old stimuli. The results from this study showed that during the test phase, there was an increase in pupil dilation to words correctly recognized as seen than those correctly recognized as new. The authors argued that this old/new pupillary effect was due to an increase in cognitive demand for the evaluation of studied words. Such findings approach the current study's objectives and demonstrate pupil response to seen and unseen stimuli. The study by Võ et al. (2008) however, was designed around the measurement of the emotionality of words and did not measure response to falsely identified words. However, it is important to note that their findings support the theory of old/new effects of pupillary response as well as the effect of cognitive load on word recognition.

The Current Study

The present study based its hypotheses on several of the directions discussed thus far. Neuroimaging, electrophysiological, and neuropsychological studies point to distinct neural processes for the encoding and retrieval of false memories compared to true (Schacter & Slotnick, 2004). Despite having subjective memory for the presentation of false items, the frontal cortex, medial temporal lobe, visual processing areas, and the parietal lobe display varying responses to word type in the DRM paradigm and other recognition tasks. Pupillary response correlates with LC activity, which connects to the cerebellum, diencephalon, brainstem, and the cortex (Sara, 2009). Therefore, pupillary response can be indicative of attention, memory, cognitive load, and emotion, thus allowing this measure to be used for further exploration of the findings from ERP, fMRI, and neuropsychology. In addition, the pupil has been shown to be reactive to stimuli of interest and novel objects as well as dilate in response to increased cognitive effort and attention (Andreassi, 2007). Taking these pupillary characteristics as well as the findings on the neurophysiological responses involved in true and false memory, the current study aimed to investigate pupillary responses during the DRM paradigm.

The DRM paradigm was employed as it has been repeatedly demonstrated to successfully produce false memory in participants (Gallo, 2006). Participants first studied 13 semantically related lists with 10 words in each list. They were subsequently tested on their memory for a selection of these words, as well as new words by responding “yes” or “no” to the question of whether the words had been previously presented. Of these new words, some were unrelated to the studied words, some were weakly related, and some were semantically-related, critical lures. During this testing or recognition phase, pupillary response was recorded during the presentation of each word, as well as to a fixation point to record the baseline pupil diameter. The pupil measurements were recorded for a duration based on the typical reaction time of the pupil, an average of 500 to 1000 ms (Andreassi, 2007). In order to compare pupil dilation to behavioral responses, the accuracy and response time of word recognition were recorded. This behavioral data also helped to ensure that the pupillary responses were due to the effects of the DRM paradigm and not to extraneous factors.

In order to ensure internal validity, a control group was also tested. This group was exposed to the same words from the recognition phase of the DRM paradigm, however, was not tested on their memory. Instead, they were asked to rate the words according to their frequency in the Norwegian language. This enabled the measurement of pupil dilation to the words themselves and a comparison with dilation to the words in the experimental group. The control group was selected to engage in this word frequency task because pupillary responses have been shown to diminish without task engagement (Andreassi, 2007). The experimental group received feedback on their accuracy after each response, so as to keep the pupil responsive.

This study aimed to successfully induce false memory with the DRM paradigm evidenced by decreased accuracy for the critical lures. It was hypothesized that pupillary response would vary depending on word type in the DRM, indicating a memory component of the pupil and the ability to use this method to study false memory.

It was predicted that pupil dilation to the seen words would be greater than dilation to the unseen and unseen-weak words (seen > unseen, unseen-weak). This was expected as participating in a memory task elicits a phasic response of the pupil (Granholm & Steinhauer, 2004). The seen words were hypothesized to demand more attention and evaluation causing greater cognitive difficulty than the unseen words, which would be marked by increased pupil dilation. In addition, the seen words were presumed to require additional attentional and cognitive processing since they would engage memory retrieval for a neural trace whereas the unseen words would not, due to their novelty.

It was also hypothesized that the critical lure would evoke a greater pupil diameter than the unseen and unseen-weak words, (lure > unseen, unseen-weak) similar to that of the seen words. The lures and seen words were most salient to the task, suggesting that they should elicit a greater pupillary response than the unseen words and demonstrate the detection of a new attentional target. Despite the lure words being novel like the unseen and unseen-weak words, the critical lures were semantically similar to the seen words, requiring more attention and evaluation from the participant. In addition, explicit recognition of the lures would have likely engaged memory retrieval processes. The unseen, unrelated or weakly related words, on the other hand, needed no information retrieval and were therefore easier to discard.

This study was also aimed at finding out whether or not the lure words would elicit a greater pupillary response compared to the seen words (lure ≥ seen). Past research demonstrates there are certain brain regions which respond to both true and false memory, and others that show activity to just one or the other (Schacter & Slotnick, 2004). The current experiment sought to measure whether false memory, i.e. the lure, would cause a larger pupil diameter than true memory, i.e. the seen words, or whether their pupillary responses would be comparable. Greater dilation to the lure would indicate increased attention and cognitive load to process, evaluate, and attempt to locate the memory source for these words. Similar dilation however, would point to an equivalent memory retrieval process.

Methods

Participants

Participants were recruited from the University of Oslo as well as through social networking and were not compensated. They were randomly assigned to either the control (N= 10; females= 7) or experimental condition (N= 33; females= 24). Three of the participants from the experimental group were excluded due to poor eye calibration, leaving 30 participants (N=30; females= 21). Ages in the experimental group ranged from 19-40 (M=24.87, SD=4.38). For the control group, ages ranged from 24-33 (M=27, SD=3.02). All of the participants were fluent in Norwegian and had normal or corrected-to-normal vision.

Materials

The current study employed the DRM paradigm to create false memories and used Roediger and McDermott’s original paradigm as a template in order to maintain validity and comparability (Gallo, 2006, 2010; Roediger & McDermott, 1995). Words for the study lists and the recognition test were created in Norwegian and not translated from English, as critical lures are specific to every language. This has been demonstrated by past studies to be a valid method for using the DRM paradigm in other languages (Brennen, Dybdahl, & Kapidzic, 2007; Gallo, 2006).

Thirteen critical lures were used to create word lists with 10 semantically related words for each lure as presented in Appendix A. Ten of these critical lures were the Norwegian equivalent of the English lures used in the original Roediger and McDermott experiment (Roediger & McDermott, 1995). The 10 associated words within each list were chosen based on being most strongly related to the critical lures. In addition, some words were chosen and changed from the English version to fit into Norwegian culture. For example, in the word list for the lure “king,” the name “Harald” was an associate as this is the name of the

King of Norway. The name of the Queen of Norway, "Sonja," was the weakly related word used in the recognition phase.

For the recognition phase, a total of 85 words were presented (Appendix B). Of these, 39 of the words were from the study phase, with three words from each word list. The remaining 46 were 13 new words that were weakly related to the studied word list, one per list, the 13 critical lures, and 20 new words unrelated to any of the lures or lists. In order to verify that the studied words and the recognition phase words would illicit false memories to the same degree as their English associates, a pilot test was conducted. Twenty-five participants were tested and lists were adjusted repeatedly to ensure a reliable and valid Norwegian version of the DRM paradigm.

Apparatus

Pupillary responses and eye movements were recorded for the participant's left eye with the use of the Remote Eye Tracking Device (RED), built by SMI SensoMotoric Instruments®. Data and measurements were collected with I-View Software©, which was also developed by SMI. The RED II records eye tracking data at a rate of 250 Hz (Laeng, et al., 2011; Laeng, et al., 2007). This is approximately every 20 ms and is done so from a distance of .5-1.5 m, with a resolution better than .1 degree. In addition, the RED II can detect changes in pupillary size as small as 0.0044 mm (according to pupil size measurements from an artificial eye with a static pupil that SMI has performed to estimate the inherent system noise of the measurement equipment as a function of camera image noise, noise from algorithms, and noise and error from distance measurements). The RED II operates by determining the position of the pupil and the corneal reflection and is done so with an infrared-light-sensitive video camera that is unaffected by room lighting. Pupil diameter was expressed as the average of the vertical and horizontal output coordinates of the pupil diameter recorded every 2 ms in an ASCII file. A separate computer was placed in front of the participant displaying the DRM paradigm with E-Prime© software while the participant was seated with their chin and forehead supported by a headrest, reducing movement. Participants gave responses during the experiment via keyboard, which was placed in front of the RED II.

Procedure

Participants were all tested in the same quiet, windowless, and remote room. They were first explained the nature of the study and then seated in front of the eye-tracking machine. The eye tracker was adjusted for the height of the participants and they were instructed to remain as still as possible during testing. They were also informed that they had the option at any point to stop the experiment and be removed from the study. During testing, the participant had a wall on one side and a cubicle partition on the other, dividing them from the experimenter. The experimenter, who remained silent, was present throughout testing adjusting pupil and corneal reflection thresholds. All participants were debriefed on the aims and hypotheses of the study after testing and any questions were answered.

The experimental group began with instructions explaining that the study would be comprised of three parts and not to hesitate to ask questions. The participants were also instructed that the first section would consist of a presentation of several lists of words and to be focused and attentive as memory for these words would be tested subsequently. The study phase was blocked with 13 lists and 10 words in each list presented in sequential order. When the participant was ready, they began the study by pressing any key on the keyboard. The study phase began with a fixation point lasting for 500 ms, followed by a blank screen for 400 ms, then the study word for 1500 ms, and then another blank screen for 400 ms. In addition, after each word list a dash was presented for 1500 ms dividing the word groups from each other. This loop continued until all of the 130 words were presented. Both the fixation points and the study words were presented in the center of the screen in black, size 32 Courier New font on a white background.

After the study phase, there was a brief pause for eye calibration, which was approximately 3-5 minutes depending on the individual. The eye-tracking device was adjusted for eye focus, pupil and corneal reflection thresholds, as well as eye movement positions. Once calibration was finished, the recognition phase began with instructions informing the participant that words would follow and they were to decide whether or not the word was presented earlier in the study phase. They did so by pressing specific keys on the keyboard. Pupillary responses and eye movements were recorded for this phase and obtained by I-View as sets. There were 170 sets, half of which were eye responses to fixations in order to establish baseline dilation, and the other half were responses to word presentation. The fixation (a centered string of 6 “x” letters) was displayed after the instructions, for 500 ms, during which data was acquired. Following this was another fixation point for 100 ms and then a blank screen for 400 ms, both unrecorded. This was followed by the presentation of one recognition stimulus.

For these recognition stimuli, there were a total of 85 words presented as mentioned above. Thirty nine of these were “seen” words, 13 “lure” words, 20 “unseen”, and 13 new weakly related words, or “unseen-weak.” The order of presentation was randomized, with each word being presented for 3000 ms. After the participants decided with “yes” or “no” responses as to whether they had previously seen the presented word, feedback was given. Either a correct or incorrect response was displayed as well as the response time and the percentage of accuracy over the entire phase. If the participant failed to respond to the word in the allotted 3000 ms, the response was automatically deemed incorrect. Feedback was displayed for 1500 ms with correct responses in blue font and incorrect in red. In summary, this recognition phase was a loop consisting of instructions, a baseline fixation, a second fixation, a blank screen, the recognition stimulus, and feedback. This loop was repeated until all of the 85 words had been presented.

The control group saw the same 85 words that were presented in the recognition phase of the experimental condition in a random order. After undergoing the same eye calibration procedure as the experimental group, instructions were presented informing the participants that they would see a fixation followed by a word. They were instructed to decide whether the word was used often in the Norwegian language and respond via keyboard with “yes” or “no.”

Following the same procedure as the experimental group, data was acquired for response to fixations and to word stimuli, totaling 170 sets. The fixation was presented for 500 ms followed by an unrecorded fixation point for 100 ms and a blank screen for 400 ms. The words were displayed for 3000 ms and directly after, the instruction screen asked for a response as to whether or not the word was commonly used in the language. At the end of this loop, there was a blank screen for 400 ms. Behavioral responses were not recorded, as they were insignificant to the results, however were used to engage the participants in the procedure and keep them focused throughout testing.

Results

Behavioral Findings

The accuracy rates (in percentage % correct) and response times (RTs) in the DRM task were analyzed for the experimental group in the recognition phase. A first repeated measures analysis of variance (ANOVA) was conducted to compare the effect of Word Type (lure, seen, unseen, and unseen-weak) on the percentage of Accuracy in the recognition phase. There was a significant effect for Word Type on Accuracy, $F(3, 29) = 97.17$, $p < .0001$. The means and standard deviations (SDs) for each Word Type are presented in Table 1 and Figure 1. Paired t-tests were conducted to measure the difference in Accuracy mean between Word Types without post-hoc corrections (since specific predictions had been made from the outset). Significant differences were found between each Word Type, lures ($M=37.18$, $SD=15.13$) and seen words ($M=72.31$, $SD=11.24$), $t(29) = -8.67$, $p < .0001$; lures and unseen words ($M=88.67$, $SD=12.79$), $t(29) = -14.27$, $p < .0001$; and lures and unseen-weak words ($M=80.26$, $SD = 11.90$), $t(29) = -13.26$, $p < .0001$. There were also significant differences between seen and unseen words, $t(29) = -5.324$, $p < .0001$; seen and unseen-weak words, $t(29) = -2.71$, $p = .01$; and unseen and unseen-weak words, $t(29) = 3.70$, $p = .0009$.

Table 1

Experimental group Accuracy for Word Type in the DRM paradigm presented in percentage

Word Type	N	Mean	SDs
Lure	30	37.18	15.13
Seen	30	72.31	11.24
Unseen	30	88.67	12.79
Unseen-weak	30	80.26	11.90

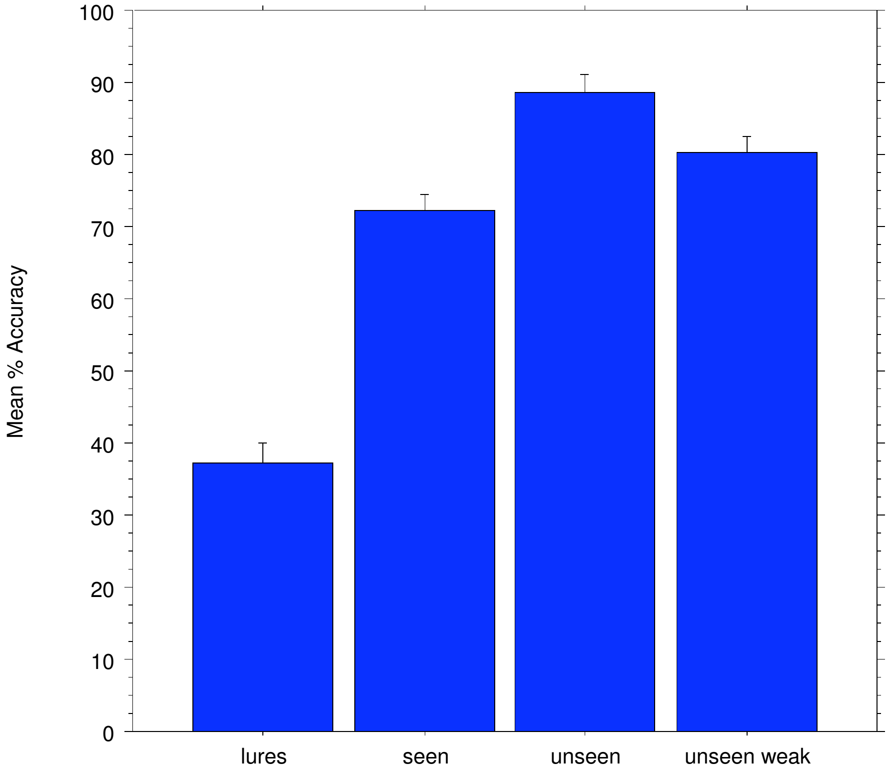

Figure 1. Experimental group mean Accuracy for each Word Type in the DRM paradigm presented in percentage. Error bars represent ± 1 standard error.

To fully measure the behavioral effects of the DRM paradigm, the time used to correctly recognize or correctly reject words in the recognition phase was also analyzed. A repeated measures ANOVA was used to evaluate RT differences between Word Types. There was a significant effect of Word Type on RT, $F(3, 29) = 26.63$, $p < .0001$. Means and SDs are presented in Table 2 and Figure 2. Paired t-tests were conducted on each of the Word Types, finding significant differences between lure (M= 1348.61, SD= 391.01) and seen words (M=1042.43, SD = 211.18), $t(29) = 6.601$, $p < .0001$; lure and unseen words (M=1077.05, SD=250.31), $t(29) = 6.047$, $p < .0001$; lure and unseen-weak words (M=1157.32, SD = 241.64), $t(29) = 4.016$, $p = .0004$. Significant differences were also found between seen and unseen-weak words, $t(29) = -4.922$, $p < .0001$; and unseen and unseen-weak words, $t(29) = -2.642$, $p = .01$. No significant differences were found however, between RT of seen and unseen words, $t(29) = -1.489$, $p = .1474$.

Table 2

Experimental group Response Times for correct responses in the DRM paradigm presented in milliseconds

Word Type	N	Mean	SDs
Lure	30	1348.61	391.01
Seen	30	1042.43	211.18
Unseen	30	1077.05	250.31
Unseen-weak	30	1157.32	241.64

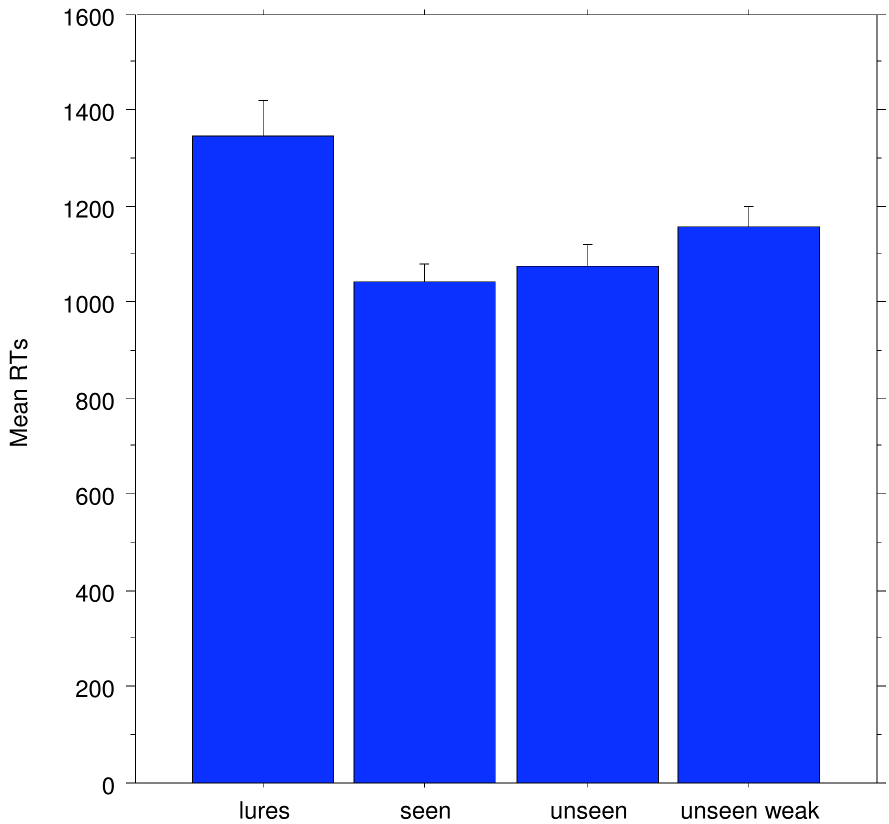

Figure 2. Experimental group mean Response Times for correct responses in the DRM paradigm presented in milliseconds. Error bars represent ± 1 standard error.

Pupillometric Findings

The pupillary response recordings for both the experimental and control group were first converted from pixels into millimeters by dividing values by a constant of 16.72. The x and y axis values for each of the 170 recording sets were then averaged to obtain pupil diameter and separated by stimulus type, (lure, seen, unseen, unseen-weak words, and the fixation point or baseline). A repeated measures ANOVA was conducted to measure effect of Stimulus Type on Pupil Diameter in the experimental group. The mean Pupil Diameter was significantly different between Stimulus Type, $F(4, 29) = 30.177$, $p < .0001$, (Table and Figure 3). Paired t-tests were also conducted to analyze differences between the means of each Word Type. Significant differences were found for the lure ($M = 3.853$, $SD = .551$) and the unseen words ($M= 3.816$, $SD =.542$), $t(29) = 5.135$, $p < .0001$; the lure and the unseen-weak words ($M = 3.831$, $SD = .542$), $t(29) = 3.395$, $p = .0020$; and the seen ($M= 3.845$, $SD = .553$) and the unseen, $t(29) =4.451$, $p = .001$. Mean Pupil Diameter by Word Type also differed significantly between unseen and unseen-weak words, $t(29) = -2.083$, $p = .046$; and the difference between seen and unseen-weak words was marginally significant, $t(29) = 1.962$, $p = .0594$. However, no significant difference was found between lure and seen word Pupil Diameters, $t(29) = 1.234$, $p = .2271$.

Table 3

Experimental group Pupil Diameter to Stimulus in the DRM paradigm presented in millimeters

Stimulus	N	Mean	SDs
Baseline	30	3.750	.563
Lure	30	3.853	.551
Seen	30	3.845	.553
Unseen	30	3.816	.542
Unseen-weak	30	3.831	.549

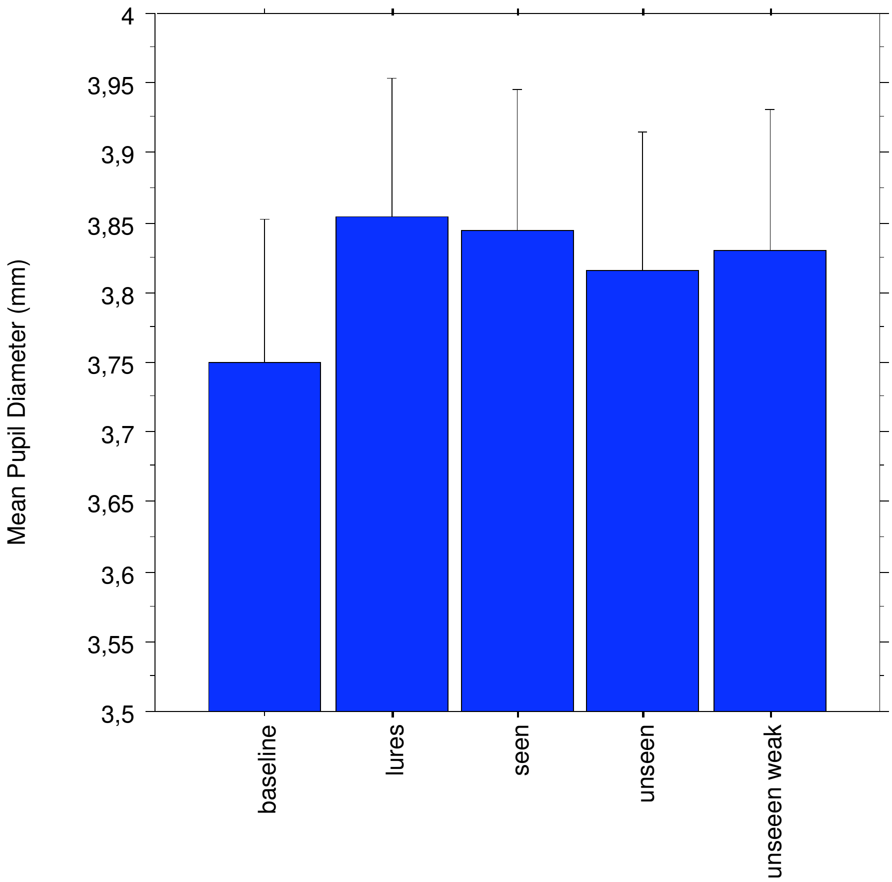

Figure 3. Experimental group mean Pupil Diameter by Stimulus in the DRM paradigm presented in millimeters. Error bars represent ± 1 standard error.

Pupil Diameter to Word Type in the experimental group was also baseline corrected by subtracting the baseline mean from response producing the mean Pupillary Change. A repeated measures ANOVA was conducted on these values, however yielded similar findings to the ANOVA done on the Pupil Diameter means, $F(3, 29) = 11.153$, $p < .0001$. Preliminary analysis was run to measure the effect of Gender on Pupillary Response, however no significant difference was found. Due to the participant's small variance in age, this was not considered a variable.

Pupil Diameter was also analyzed for control participants with a repeated measures ANOVA finding $F(4,9) = 7.745$, $p = .0011$. Upon further analysis, paired t-tests revealed that the mean baseline Pupil Diameter varied significantly from the Word Types, however there was no significant difference between the Pupil Diameter by Word Type. A repeated measures ANOVA was also conducted with Group (Controls, Experimental) as the between-subjects factor and pupil diameter to Stimulus Type (Seen, Lures, Unseen, Unseen-weak, Baseline) as the dependent variable. The effect of Group did not reach significance, F (1,38) = 3.03, p = .09, however more importantly, a significant interactive effect of Group and Stimulus Type was found, F (4,152) = 24.496, p < .0001. Figure 4 presents the mean Pupil Diameter by Stimulus for both the control group and the experimental group, showing pupillary response in controls reduced compared to the experimental group. The only exception was response to baseline, meaningless strings of symbols, which provoked similar pupillary responses in both groups.

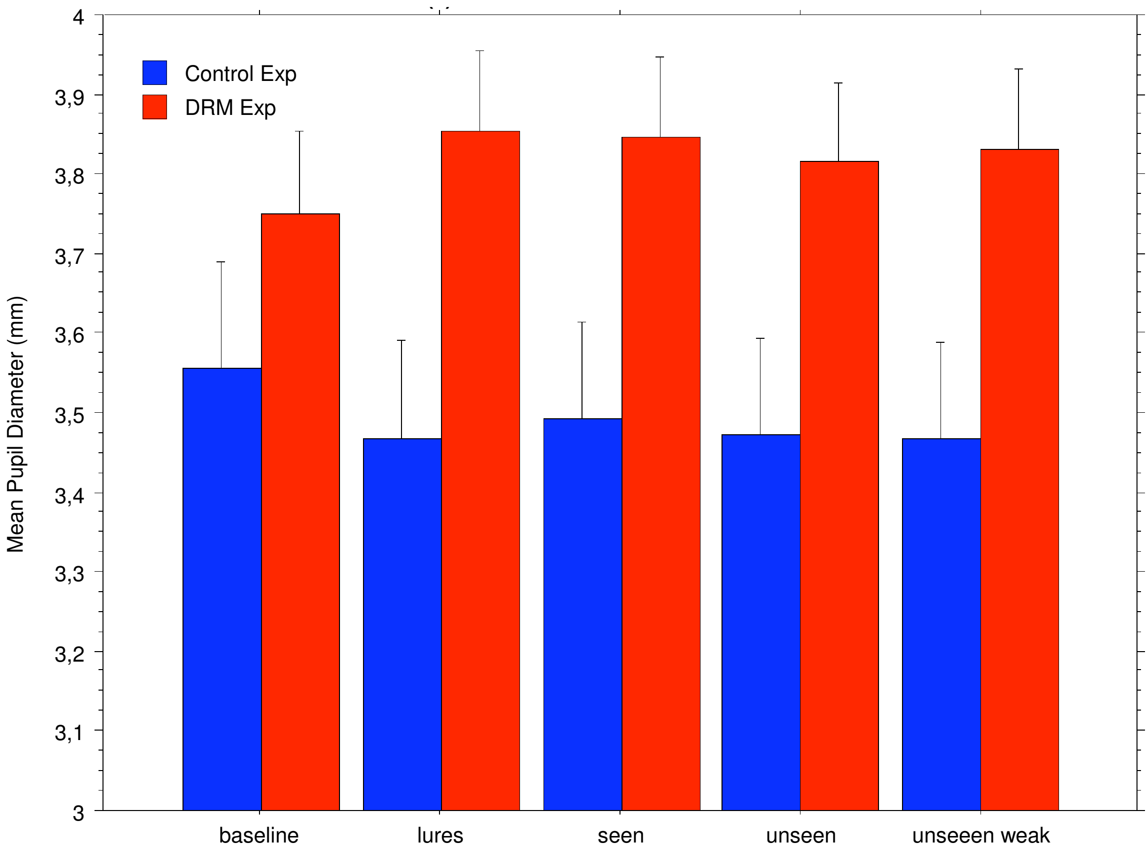

Figure 4. Mean Pupil Diameter by Stimulus for both the control group and the experimental group presented in millimeters. Error bars represent ± 1 standard error.

Discussion

The current study measured pupillary response to the DRM paradigm and found a significant effect of word type on pupil diameter. Finding pupillary response to vary depending on the word type presented, demonstrates the effectiveness of this method in testing memory illusions.

A significant increase in pupil diameter to seen words compared to unseen and unseen-weak words was also found (seen > unseen, unseen-weak,) supporting the second hypothesis. Further, the third hypothesis was also upheld finding greater pupil dilation to the lure words compared to the unseen and unseen-weak words (lure > unseen, unseen-weak).

The current study also aimed to investigate whether the lure words would elicit larger pupillary responses than the seen words. While the pupil diameter to lure words tended to be greater than that to the seen words, a paired t-test revealed no significant difference between these responses. However, it should be noted that the obtained significance value of $p = .23$ is not strong enough support to conclude in favor of the null hypothesis. In fact, when individually evaluating each participant's mean pupil diameter by word type, a significant difference between the lure and the seen words (lure > seen) was found for about half of the group. This suggests that with an increase in participants and methodological improvements (e.g., more word lists and/or more sensitive lists) a statistical difference could have emerged.

It is also important to acknowledge the behavioral results of the experimental group in this study. The analysis showed that the DRM paradigm used in this experiment was successful at producing false recognition for the semantically related lure. This is evidenced by the significantly reduced accuracy of recognizing the lure words as new, compared to the seen, unseen, and unseen-weak words. Participants identified the lure as previously seen an average of 62.82 %, a rate similar to the correct identification of seen words, which was 72.31 %. The effects of the DRM on the current study's participants are further demonstrated by the difference in the time used to respond correctly to the word types. Participants used significantly more time to accurately identify the lure words as new, than they did the unseen and unseen-weak words, and more time than to correctly recognize the seen words.

This study aimed to uncover the relationship between memory and the pupillary response. Moreover, it aimed at finding whether there were dilation differences between true and false memories. Because the behavioral data revealed increased false memory for the lure words (as evidenced by decreased accuracy rates compared to other word types) it can be assumed that the pupillary results were not due to artifacts but due to the effect of the DRM paradigm. It can also be assumed that the pupillary responses did not reflect a response to the words themselves because there was a lack of significant difference between mean pupil diameter by word type in the control group. In addition, there was a significant interactive effect between pupil diameter to stimulus type and group. These findings demonstrate that pupillometry can be used successfully in conjunction with the DRM paradigm and most importantly, that they can give insights into the characteristics of memory and the pupil response.

It can be interpreted from the results that the pupillary response does reveal a memory component, as highlighted by varying pupil size between unseen and seen words. However, since the lure elicited a similar pupillary response as the seen words, (a similar reaction to false recognition and true) this study seems to suggest that these two are not distinguished within the memory system. It could be inferred that both false and true recognition share a similar retrieval process, as the lure and the seen words displayed similar degrees of dilations. However, the previous studies (e.g. neuroimaging) discussed supported a distinction within the brain memory system for retrieving veridical versus illusory information. Thus, one possibility is that pupillometry may not be a very sensitive method for detecting such an effect and that larger participant numbers are needed to reveal a pupil response to false, rather than true memories.

A pupil's response to the novelty of the stimuli is usually seen with more passive conditions, like in repetition priming paradigms and "oddball" detection tasks, where the targets are infrequent (Andreassi, 2007; Granholm & Steinhauer, 2004; Laeng, et al., 2007). When actively engaged in a task, the pupil shows fast phasic responses and reacts more to cognitive load and difficulty (Andreassi, 2007; Granholm & Steinhauer, 2004; Kahneman & Beatty, 1966; Võ, et al., 2008). Therefore, in these active conditions, the pupillary dilation response may not respond primarily to the novelty of the stimuli, but instead be overridden by the memory processing components and task demands. Since the results of this study revealed increased pupil diameter to seen words compared to unseen, it can be interpreted that participating in the DRM paradigm requires increased engagement and mental effort.

This reasoning might also explain why the current study found contradictory results to those found by Laeng et al. (2007). Their study on amnesic patients and pupillary responses found increased pupil diameter for new images compared to previously seen images despite no explicit memory (2007). The current study found an opposite effect with seen words eliciting a greater response than the unseen words, with the exception of the lure. These contrasting findings may be due to the nature of the task as well as the characteristics of the participants. The patients in the Laeng et. al study were asked whether or not they had seen the picture before, and two of the three were asked to rate their confidence in their response. It is possible that this task was not as demanding as the DRM paradigm, causing a more passive, tonic response of the pupil, whereas the DRM elicited an active, phasic, attentively oriented response. Another possibility for the divergence in results could be that the participants in the Laeng et al. study suffered from amnesia. These patients had none to severely-reduced explicit recollection for seeing any of the images. This lack of conscious awareness for memories may have contributed to the more passive-acting pupillary response, which essentially exposed a repetition priming effect on pupil response. It could also be that the memory task in this study was not as cognitively demanding as the DRM because of the severe memory deficits, which lower the patients' motivation to engage in repeated unsuccessful attempts of active retrieval.

Further demonstrating a memory component of the pupil, the current study replicated some of the findings observed by Võ et al. and supported their hypothesized "pupil old/new effect," (2008). These researchers were successful in finding increased pupil dilation to words correctly identified as seen compared to words correctly identified as new, corroborating the ERP parietal old/new effect. The results from the current study could be understood in this context, as previously seen words evoked a greater pupil diameter than the unseen and unseen weak words. Unlike that of Võ et al., the old/new effects in the current study were found for accurate and inaccurate recognition, as a post-hoc analysis found no difference in pupillary response based on accuracy.

Võ and colleagues interpreted the increased dilation to seen words as an indication of increased cognitive demand for the evaluation of a previously studied word (2008). Their study did not incorporate semantically similar lure words to induce false memory, so it is unclear how these old/new effects translate to the DRM. However, their interpretations could be applied to the current study, as well as shed light on finding increased dilation to the lure word. The lure words caused an "old" effect with responses similar to those of the seen words and not those of the unseen words, it can therefore be assumed that these lure words engage a similar memory retrieval process as the seen words. This also indicates that the lure words required more evaluation than the unseen words, and could help to explain why pupil size to the lures was greater than to the unseen, which may have been easier to identify as new.

Evaluation for old seen words, either true or false, raises another important point regarding a memory component for the pupil. Due to the fact that retrieving information or details from memory is considered to be a more demanding process, an increase in pupillary response during a recognition task could be indicative of this process (Võ, et al., 2008). More specifically, the retrieval of memories engages a neural pattern to trace and recover the information, or ‘sensory-reactivation’ (Schacter & Slotnick, 2004). When presented with words to evaluate in the DRM, the seen words should engage these processes. The seen words should increase pupil diameter more than the unseen words, as this retrieval is more cognitively demanding; the current study supports this pattern.

The larger pupil diameter in response to the lure rather than the unseen words can also be understood in this memory retrieval context. The semantic similarity of the critical lures to the seen words caused participants to evaluate and attempt to retrieve information from their memory more than the unseen words, which were easier to discard as new. This helps to explain why the critical lure elicited a pupil response with greater similarity to the seen words than to the unseen words, as they engage the same retrieval mechanisms that process the seen words.

It is also important to consider the differences between information retrieval for the lure words compared to the seen words. It may be that when the participant is attempting to retrieve the memory and information for the lure word, there is no real memory or neural “tag”. Therefore, if the memory is false and there is no detail or source for the word, the retrieval is “noisy” and more attentional resources may be demanded. This sorting of information that has not been encoded creates conflict, possibly increasing cognitive demand. It is these extra attention processes that could be the cause of increased pupil diameter, as increased cognitive load has been shown to cause dilation (Andreassi, 2007; Dionisio, et al., 2001; Granholm & Steinhauer, 2004; Kahneman & Beatty, 1966). This could also be related to the source-monitoring framework as the critical lure may cause the participant to attempt to locate the source of the word because of its familiarity. Due to the lack of source or information of detail for the lure word, there could be increased information processing, which in turn, causes increased pupil dilation. This interpretation describes another possibility for the increase in pupil size to the lure compared to the unseen words, but also indicates that with further testing, pupillary response to the lure word may reach a significant difference due to this additional retrieval “conflict”.

Another component that the results from the current study highlight is that of attentional processes, by way of the LC-NE system. Pupil response correlates with activity in the LC-NE system, which is highly influential on functioning in most of the brain, and in turn, mental activity (Corbetta, et al., 2008; Sara, 2009). This system also gives input to the ventral attention network. Due to this network and the LC-NE system’s role in directing attention to salient and behaviorally relevant stimuli, increased pupil response to the lure and the seen words indicate that these words grabbed more attention than the unseen words and that the attention system detected these words as a new target for attention.

In addition, when engaged in a task, the LC-NE system responds to irrelevant stimuli by filtering them out and reorienting attention to the target stimuli (Corbetta, et al., 2008; Sara, 2009). Decreased pupil diameter to the unseen words may signify that these words were treated by the LC-NE system as distractors, keeping increased attention on the most salient information to the task, i.e. the lures and the seen words. It is interesting to note that despite the lure words being new like the unseen words, they were not treated by the attention system as such. Instead, they drew attention similar to the seen words as they may have been regarded as a salient “target” and not a “distractor.” Even some of the earliest studies using pupillometry found a correlation between the interest value of stimuli and pupil size (Andreassi, 2007; Hess & Polt, 1960). Considering that the seen words and the lures appear to engage increased evaluation and memory retrieval (as evidenced by the behavioral results), it is reasonable to assume that these words are of greater interest to the attention system than the unseen, easier to process words.

While the memory component of the pupillary response has already been discussed, the LC-NE system’s involvement in memory processing and input to the hippocampus adds to the above arguments as well as those regarding attention (Sara, 2009). It has been theorized that just as the ventral attention network responds to relevant stimuli, it also responds to memory retrieval, as this can also be a relevant target grabbing its attention (Corbetta, et al., 2008). When processing memories, the ventral network also acts to stop the reorientation to new stimuli. In addition, the objects that attract the most attention are those that are relevant to long-term memory or those that long-term memory deems important (Corbetta, et al., 2008). Therefore, increased pupil size to the critical lures may signify that these words trigger memory processing and subsequently, more attention, more LC-NE activation, and more pupil dilation.

As mentioned earlier, the LC modulates PFC activity via norepinephrine (Corbetta, et al., 2008; Sara, 2009). Pupil response can therefore be considered an indication of not only LC-NE activity, but also of the PFC. Moreover, processes that have been documented to cause PFC activation are also those that increase pupil size, e.g. cognitive processing and demand, as well as task difficulty, demonstrated in past studies with multiplication tasks, short-term recall, working memory tasks, and memory load (Andreassi, 2007; Granholm & Steinhauer, 2004; Kahneman & Beatty, 1966). Hence, increased pupillary response to the lure words compared to the unseen words indicates that these lures increased PFC activity. This is a reasonable concept as these words posed the greatest conflict, difficulty to process, and cognitive demand and load. This implication is supported by the behavioral data that revealed participants to use significantly more time to correctly identify the lure words as new. This response time signifies some type of monitoring and decision-making and indicates that the lure words required more cognitive effort. These monitoring processes corroborate the past studies with ERP and fMRI discussed earlier, which found the frontal lobe to be engaged in false memory paradigms and reduce illusory recognition (Gallo, 2010; Parkin, et al., 1996; Schacter, et al., 1997a; Schacter & Slotnick, 2004; Verfaellie, et al., 2004). It is important to point out that the seen words also elicited increased dilation and possibly PFC activity compared to the unseen words. This also implies that, when presented with these seen words, the LC-NE system and the PFC were engaged to evaluate, retrieve, and make a decision about the source of the word.

It is important to also consider the role of the ACC in false memory processes as well as pupillary response. This brain structure has been found to play a role in monitoring conflict, cognitive control and load, error detection, performance monitoring, and executive attention (Critchley, Tang, Glaser, Butterworth, & Dolan, 2005; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). In addition, activation in the ACC has been found to correlate with autonomic arousal measured by pupillary response (Critchley, et al., 2005). Critchley et al. measured ACC activity with fMRI in response to error and conflict on the Stroop task, revealing a link with pupil dilation. This finding indicates the ability to interpret pupillometric results as an indirect indicator of ACC activity. This inference, albeit presumptuous, indicates that just as pupillary response can be a marker of PFC activation, the same may be true for the ACC. This is also supported by findings demonstrating pupil size increasing to similar stimuli and tasks that activate the ACC, be it in response to the Stroop task (Critchley, et al., 2005; Laeng, et al., 2011) or recently, in response to errors and perceived mistakes during a saccade task (Wessel, Danielmeier, & Ullsperger, 2011).

As discussed previously, the ACC has been found to activate during the encoding and retrieval of false memories (Gonsalves, et al., 2004; Okado & Stark, 2003). False memories give rise to additional conflict, effort, and a demand for attention and cognitive control; processes found to be mediated by the ACC. Furthermore, the ACC has been described as showing response to memories that are linked to increased conflict in false memory paradigms (Okado & Stark, 2003). These findings, coupled with those of ACC activity correlating with pupillary response, can help to explain some of the results in the current study. Critical lures may have caused greater conflict and need for response control than their unseen counterparts, due to their semantic similarity to seen words as well as "noisy" memory retrieval. An increased executive attention would then cause increased activation in the ACC as well as in the autonomic response, i.e. pupil dilation.

While many studies measuring pupillary and ACC activation to conflict have focused on the role of conscious awareness of error making (Critchley, et al., 2005; Wessel, et al., 2011), there is evidence that the ACC does show activation regardless of external feedback (Holroyd et al., 2004; Ridderinkhof, et al., 2004). In other words, the error can be in the form of an internal process, possibly in this study, locating a memory trace that does not exist or the conflict between what seems familiar and what is veridical. While these concepts support the current study's findings of increased pupil dilation to lure compared to unseen words, it is inconclusive as to whether the lure and the seen words differ in their engagement of the ACC and autonomic arousal. In the study of Okado and Stark (2003) using a reality-monitoring paradigm with fMRI, false memories caused greater activation in the ACC whereas true memories did not. Assuming the lure words caused greater conflict and cognitive effort than the seen words, these words should have caused greater pupillary response. This is something that needs to be further explored in order to measure whether false memory does increase pupil size more than true memory.

Limitations

Despite the compelling findings from the current study, there are some limitations that warrant mention. The amount of participants, while typical for pupillometry studies, may have hindered the results to some degree. As discussed earlier, although differences between the mean pupil diameter for the lure words and the seen words did not reach significance, it is possible that this tendency is a true reflection of the pupillary response in the DRM. Increasing N may have led to statistically significant results, as half of the experimental group was found to have significantly greater pupil dilation to the lure words than the seen words.

Another limitation possibly contributing to this lack of significance may have been the stimuli itself. While the DRM word lists were shown to successfully cause false recognition of the lures in this study, the materials used may have added to the similar pupillary responses between the lure and seen words. For instance, by adding more word lists to the study phase and the testing phase, a difference may have emerged. There were only 13 critical lures in the testing phase compared to 39 seen words. With more pupillary response values to lure words

(20 frames for each stimulus is typical) the speculated difference may have been found (Andreassi, 2007).

Pupillary responses have been demonstrated to decrease at the beginning and at the end of an experiment (Andreassi, 2007). Fatigue can also affect pupillary response with tiredness causing pupil constriction. Interest is also required to maintain the response, which can also decrease with overexposure to stimuli. The current study did not account for either of these factors, and it is unknown to what extent they might have influenced the results. It is important to note however, that there were significant differences between pupil diameters to baseline and to word type, so fatigue and task timing may not have had any impact.

Implications for Future Work

The results from the current study raise many important questions and directions for future research. As this study was the first to combine the DRM paradigm with pupillometry, it is first important to replicate the findings and expand the number of participants. This may expose significant differences between the pupillary responses to the lure words compared to the seen words, as well as reveal more substantial evidence for the neural differences and similarities between true and false memories.

It would also be advantageous to combine pupillometry with electrophysiology and neuroimaging in studying memory distortion. Recording pupillary responses during fMRI and ERP has been shown to be successful in linking pupillary responses with various brain activations and processes (Critchley, et al., 2005; Sara, 2009; Sterpenich, et al., 2006; Wessel, et al., 2011). By measuring pupillary response in conjunction with these measures, patterns in the timing of reactions as well as similarities between pupil dilation and neural processes may be revealed. This would also allow for a better comparison between the many previous studies on false memories with ERP and fMRI and the results of the current experiment. Since it was proposed that the pupil may have old/new effects similar to those measured with ERP, conducting a study with both ERP and pupillometry might present interesting findings as to the exact similarities between old/new effects in both these measures (Võ, et al., 2008).

Once the results of this study are replicated and the pupillary components of false memories are better understood, this experimental design could be extended to other populations. For example, individual differences can be measured as well as the effects of various psychological disorders. Specifically, the DRM paradigm and pupillometry have been used separately to find age and intelligence effects, along with effects due to mental illnesses like depression, schizophrenia, Asperger's syndrome, posttraumatic stress disorder (PTSD), and others (Andreassi, 2007; Brennen, et al., 2007; Gallo, 2006; Granholm & Steinhauer, 2004). By combining the DRM paradigm and pupillometry to study the abovementioned clinical disorders and individual characteristics, more details regarding false memories can be found as well as features related to various diagnoses.

One particular area within the field of psychology where this research could play an important role, is in studying the influence of trauma on memory. As was discussed in the Introduction, the study of false memories has had a significant effect on understanding and treating childhood abuse memories (Loftus & Davis, 2006). While it has been debated whether the DRM paradigm can be applied to autobiographical memories, this paradigm has demonstrated that it successfully induces memory illusions that share similar processes to those in real-life situations (Gallo, 2010). By continuing research with pupillometry along the lines of the current study, it may be possible to use this method to measure memory in trauma survivors. Moreover, through gaining knowledge on pupillary responses to false memory, pupillometry may eventually be used to indicate if a memory is true or not.

This implication gains support from research on trauma survivors who show abnormal behavioral responses to the DRM paradigm with increased susceptibility to war-related false memories (Brennen, et al., 2007). This research, as well as the findings on the LC and pupillary response showing increased activity to emotional memories, points to the possibility of incorporating pupillometry with the study of false memories in these trauma survivors. Furthermore, the effect of the LC-NE system on the amygdala and the hippocampus, make pupillary response a possible measure for emotional or traumatic memory. This concept has an important place in regards to child abuse cases as well as eyewitness testimony, which has been shown to be susceptible to inaccuracies (Loftus, 1996). In fact, as discussed earlier, pupillometry has been suggested and tested on its potential to be used in lie detection (Dionisio, et al., 2001; Heaver & Hutton, 2010; Lubow & Fein, 1996). Results have found that when participants are instructed to lie or hold guilty knowledge, pupil diameter increases. While it is tempting to interpret these findings as well as those regarding false memory as an indication of the ability to use these measures to detect lying or memory distortion in the field, there are some limitations to this. In real life settings, only one person would be the subject and the number of usable stimuli (e.g., clues to a crime) may be very limited, causing statistical and methodological problems. Despite this, lie and false memory detection raise important implications for pupillometry and directions for future research. While there is still much to investigate, it is clear that by understanding the pupil's reaction to false memories, many different areas within psychology and neuroscience will benefit.

Conclusions

The current study began to explore the pupillary responses to false memories in the DRM paradigm. The results showed a significant effect of word type on pupil size with increased pupil dilation to seen words as compared to unseen. In addition, pupil diameter to false recognition or the critical lure was found to be significantly greater than the unseen and unseen-weak words. This increased lure response was similar to that of the seen words, however not significantly larger. This study may be the first to use pupillometry to measure responses in the DRM paradigm and begins to reveal valuable information regarding the neural and pupillary responses to memory. While the results of this study need to be replicated and the relationship between the lure words and seen words measured further, it is clear that memory processing can be captured by the pupillary response. There are many different interpretations and explanations for the results found, be it cognitive demand, monitoring, conflict, sensory-reactivation, attentional processes, or memory "tags." Regardless of the processes involved, these findings begin to demonstrate the pupillary responses involved in memory retrieval, decision-making, and explicit and implicit memory.

There are an abundance of uses and benefits to this research. There are still many unknown processes involved in memory distortion as well as individual differences and effects of mental illnesses. This research can help to understand false memories as well as their relation to various diagnoses. In addition, this may be of value to the general study of cognition, pupillary response, and neuroscience. Pupillometry has the advantage over other methodological measures as it is inexpensive, time sensitive, and easy to use in conjunction with other measurements, whether behavioral or neurological (Andreassi, 2007; Critchley, et al., 2005; Einhäuser, et al., 2008; Granholm & Steinhauer, 2004). Continuing to use this measurement with the DRM paradigm in the study of false memories may help to discover how memory illusions are formed and how they can be detected, helping many different populations and fields.

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Appendix A

The Norwegian word lists used in the study phase and their English translations.

	English	Norwegian	English	Norwegian
Critical Lure	Fruit	Frukt	Work	Arbeid
Word List	Banana	Banan	Job	Jobb
	Vegetable	Grønnsak	Money	Penger
	Orange	Appelsin	Office	Kontor
	Jam	Syltetøy	Factory	Fabrikk
	Dessert	Dessert	Employment	Sysselsetting
	Plums	Plommer	Leisure	Fritid
	Blueberry	Blåbær	Salary	Lønn
	Cherry	Kirsebær	Tiresome	Slitsomt
	Juice	Juice	Responsibility	Ansvar
	Salad	Salat	Colleagues	Kolleger
Critical Lure	Cold	Kaldt	Sleep	Sove
Word List	Warm	Varmt	Tired	Trøtt
	Snowflake	Snøfnugg	Dream	Drømme
	Winter	Vinter	Bed	Seng
	Chilly	Kjølig	Rest	Hvile
	Wet	Våt	Comforter	Dyne
	Ice Crystals	Iskrystaller	Tired	Sliten
	Weather	Vær	Bedtime	Leggetid
	Freeze	Fryse	Snore	Snorke
	Frost	Frost	Nightmare	Mareritt
	Shiver	Gysning	Wake up	Våkne
Critical Lure	Feet	Føtter	Music	Musikk
Word List	Toe	Tå	Tones	Toner
	Body part	Kroppsdel	Notes	Noter
	Ankle	Ankel	Singing voice	Sangstemme
	Kick	Sparke	Piano	Piano
	Sandal	Sandaler	Radio	Radio
	Socks	Sokker	Band	Band
	Jog	Jogge	Melody	Melodi
	Shoelace	Skolisse	Concert	Konsert
	Smell	Lukt	Instrument	Instrument
	Football	Fotball	Rhythm	Rytme

	English	Norwegian	English	Norwegian
Critical Lure	Happy	Lykkelig	River	Elv
Word List	Glad	Glad	Water	Vann
	Smile	Smil	Current	Strøm
	Laughter	Latter	Lake	Innsjø
	Satisfied	Fornøyd	Mississippi	Mississippi
	Delighted	Henrykt	Boats	Båter
	Positive	Positiv	Swim	Svømme
	Enthusiastic	Entusiastisk	Fishing lake	Fiskevann
	Laugh	Flire	Flood	Flom
	Satisfied	Tilfreds	Stream	Bekk
	Joke	Vits	Bridge	Bru
Critical Lure	Success	Suksess	Window	Vindu
Word List	Medal	Medalje	Door	Dør
	Proud	Stolt	Glass	Glass
	Achievement	Oppnåelse	Window pain	Rute
	Congratulations	Gratulasjoner	Shadow	Skygge
	Speech	Tale	Sill	Karm
	Friends	Venner	Curtains	Gardiner
	Rich	Rik	Open	Åpent
	Bouquet	Bukett	House	Hus
	Important	Viktig	View	Utsikt
	Diploma	Diplom	Breeze	Bris
Critical Lure	King	Konge	Needle	Nål
Word List	Crown	Krone	Thread	Tråd
	Queen	Dronning	Sow	Sy
	Prince	Prins	Eye	Øye
	Harald	Harald	Sharp	Skarp
	Dictator	Diktator	Point	Spiss
	Castle	Slott	Poke	Stikke
	Throne	Trone	Thimble	Fingerbøll
	Monarch	Monark	Haystack	Høystakk
	Chess	Sjakk	Thorn	Torn
	Leader	Leder	Injection	Injeksjon
Critical Lure	Doctor	Lege		
Word List	Nurse	Sykepleier		
	Sick	Syk		
	Hospital	Sykehus		
	Patient	Pasient		
	Stethoscope	Stetoskop		
	Operation	Operasjon		
	Clinic	Klinikk		
	Cure	Kur		
	Office	Kontor		
	Surgeon	Kirurg		

Appendix B

The Norwegian words used in the recognition phase and their English translations.

	English	Norwegian	English	Norwegian
Critical Lure	Fruit	Frukt	Work	Arbeid
Seen	Blueberry	Blåbær	Factory	Fabrikk
	Jam	Syltetøy	Salary	Lønn
	Banana	Banan	Job	Jobb
Unseen-Weak	Seeds	Frø	Boss	Sjef
Critical Lure	Cold	Kaldt	Sleep	Sove
Seen	Chilly	Kjølig	Bedtime	Leggetid
	Weather	Vær	Tired	Trøtt
	Warm	Varmt	Rest	Hvile
Unseen-Weak	Blanket	Teppe	Pillow	Pute
Critical Lure	Feet	Føtter	Music	Musikk
Seen	Kick	Sparke	Melody	Melodi
	Toe	Tå	Tone	Toner
	Jog	Jogge	Piano	Piano
Unseen-Weak	Slippers	Tøfler	Orchestra	Orkester
Critical Lure	Happy	Lykkelig	River	Elv
Seen	Enthusiastic	Entusiastisk	Water	Vann
	Glad	Glad	Fishing lake	Fiskevann
	Satisfied	Fornøyd	Mississippi	Mississippi
Unseen-Weak	Party	Fest	Nile	Nile
Critical Lure	Success	Suksess	Window	Vindu
Seen	Congratulations	Gratulasjoner	Door	Dør
	Metal	Medalje	Shadow	Skygge
	Rich	Rik	Open	Åpent
Unseen-Weak	Podium	Podie	Transparent	Gjennomsiktig

	English	Norwegian	English	Norwegian
Critical Lure	King	Konge	Needle	Nål
Seen	Throne	Trone	Thread	Tråd
	Crown	Krone	Sharp	Skarp
	Harald	Harald	Thimble	Fingerbøll
Unseen-Weak	Sonja	Sonja	Syringe	Sprøyte

Critical Lure	Doctor	Lege
Seen	Nurse	Sykepleier
	Patient	Pasient
	Clinic	Klinikk
Unseen-Weak	Medicine	Medisin

Unseen	Lazy	Lat
	Beach	Strand
	Persian	Persisk
	Robust	Robust
	Spider	Edderkopp
	Course	Grov
	Alcohol	Alkohol
	Spin	Snurre
	Church	Kirke
	Court	Domstol
	Sky	Himmelen
	Angry	Sint
	Narrow	Smal
	Tools	Verktøy
	Filter	Filter
	Pad	Underlag
	Hard	Hard
	Mouse	Mus
	Cotton	Bomull
	Brave	Tapper